Drying of Almonds II: Multiple Particles

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Abstract

Computational modeling is an efficient and effective tool for modeling of drying process for food products. Developing validated computational models for drying processes is essential to build energy efficient drying units, producing uniform quality of dried products. This work presents drying behavior of almonds with a specific focus on understanding interaction among multiple almonds. Eight (2x2x2) particles, and twenty-seven (3x3x3) particles arranged in the shape of a cuboid were used to conduct drying experiments in a Mettler Toledeo Moisture Analyzer unit. Experiments were conducted to measure the moisture loss data with respect to drying time using Almond kernels. Experimental data was used to understanding drying kinetics as well as variation in moisture content with respect to their positions in a cuboid. Computational fluid dynamics (CFD) based simulations were carried out for the flow, heat transfer and drying of particles in the unit. Actual geometry of individual particles were considered in simulations, to predict the variation in velocity, heat and mass transfer coefficients for all the particles. Simulations predicted moisture loss data that matches well with the experimentally measured values. Average moisture for each layer was also compared for various intermediate drying times. Simulation results captured the overall drying process for multiple particles system adequately. The results are compared with the results obtained with drying of a single almond. The approach, models and presented results will be useful for designing large scale drying units for almonds.

Keywords: Drying; almonds; CFD; transport processes; multiple particles

1. Introduction

Drying of food products is an important post-harvest unit operation, which requires large amount of energy. Drying of variety of food products is carried out to reduce their moisture levels in order to increase the shelf life, reduce the probability of developing fungi and to facilitate further processing to obtain the final product. In this work, we have considered the case of "dry fruits". Most of the dry fruits are seasonal in nature, hence post-harvest large quantities of crop needs to be stored appropriately for a long duration of time. It is important to understand drying process and influence of key process parameters on the moisture levels of dry fruits. There are few studies focusing on drying kinetics of dry fruits, Kaya et. al.[1] has studied the convective drying kinetics of kiwi fruit. Togrul et. al.[2] have studied convective drying kinetics of single apricot. Almond is also one of the widely cultivated and consumed dry fruit across the globe. It is important to ensure the drying of almonds is appropriate: more than desirable moisture will increase possibility of developing fungi, and over drying will adversely impact economics, due to loss of weight.

The design of dryer is very crucial to ensure adequate drying of food product. For better quality of dried product the moisture variation across all the particles should be within an acceptable range. To study the influence of drying process parameters, viz., air temperature, air velocity, inlet air humidity, computer simulation based modeling is recently being used regularly. Simulation results predicts the temperature and moisture variation of food products over a range of operational process parameters. With respect to quality control and selection of process parameters and design of dryer, simulation tools are most efficient in terms of cost and time. To develop models for drying simulations, it is required to understand drying kinetics, transport processes (heat and mass transfer) in the drying equipment. Another important parameter required for developing drying models is the effective diffusivity of the food product.

Earlier work was carried out for drying of a single almond kernel [3] to identify suitable drying kinetics model for almonds, estimation of heat transfer coefficient, mass transfer coefficient and effective diffusivity. The moisture variation for single almond during the drying process was predicted using simulations which matched quite well with experimental measurements. This work focusses on drying of multiple almond kernels to understand the influence of neighboring particles on the transport processes (heat and mass transfer), which in turn impacts the drying. Experimental and CFD simulations were carried out using the developed approach and drying parameters based on earlier work for single particle. Eight (2x2x2) and twenty-seven (3x3x3) almonds arranged in the shape of a cuboid were used for this work.

Application of simulation tools to understand heat and mass transport for food products are based either on two-dimensional (2D) and few three-dimensional (3D) models. There are various studies based on 2D models for drying of food products like Kaya et. al[4], Zare & Chen[5], etc. The models predict the variation of temperature and moisture of particles during the drying process using estimated transport properties. Coupling of fluid flow with drying process provides more accurate prediction of drying characteristics accounting for change in both air side and particle side temperature and moisture. Computational Fluid Dynamics (CFD) is a powerful simulation tool to predict the details flow and heat transfer for various process units. CFD is being used to model various drying processes, detailed review of same was provided by Jamaleddine and Ray[6]. CFD based models are more robust as it provides the detailed flow field within the unit. Prediction of detailed flow field is very relevant for modeling of drying process as it provides the information on variation of transport properties which influences the drying rates. There has been few recent studies based on 3D models for drying like, Ranjbaran et. al[7], for drying of deep-bed paddy drying process using CFD simulations. Conjugate heat and mass transfer for drying has been studied using CFD simulations by Khan and Straatman[8].

As the drying process is complex involving simultaneous heat and mass transfer, there is a need of models that could be applied to design and analysis of large scale drying processing units. There are limited studies considering the actual shape and cluster of particles that are being dried. ElGamal et. al[9] studied drying of single rice kernel, and Perez et. al[10], studied drying of multiple layers of rice grains with actual geometry of individual rice grain. Modeling of particles with actual shape, helps to understand the variation of transport properties along the surface. Drying rates for individual particle depends on the orientation, velocity field, temperature distribution.

The work was aimed to study the drying of multiple particles arranged in a cuboid shape, both using experiments and CFD based 3D simulations. Eight (2x2x2) particles and twenty-seven (3x3x3) particles were used to conduct the experiments. Experiments were conducted using Halogen radiator drying technology having natural convection of air flow using Mettler-Toledo Moisture Analyzer unit. Controlled experiments were conducted for drying of eight particles with two layers and twenty-seven particles with three layers for a set temperature of 75 °C. Detailed CFD models were developed to simulate flow and heat transfer within the unit and across all the particles. Influence of neighboring almond particles on heat and mass transfer coefficients was quantified by comparing the results with the single particle results from earlier work [3]. This presented experimental data, approach and models will be useful to understand the drying kinetics of almonds in different drying units. The work will provide a firm basis for extending the approach towards simulations of industrial drying units.

2. Experimental

Experiments were conducted using Halogen moisture analyzer excellence plus HX204 of Mettler Toledo, to study drying behavior of multiple almond kernels. Experiments were conducted at single set temperature of 75 °C. Details of the unit, experimental procedure, estimation of error bars, and processing of experimental data are described in the following sections.

2.1 Halogen Moisture Analyzer (HX204)

Mettler Toledo Halogen moisture analyzer excellence plus (HX204) unit is widely used to determine the moisture content of various substances. The unit works on the thermogravimetric principle. The initial weight of the sample was determined at the start of the experiment, followed by heating using halogen radiator. As the sample was being dried the instrument continuously records and displays the weight of the sample. Halogen radiator drying technology is an advancement of the infrared drying method. Halogen radiator has a glass pipe filled with halogen gas as the heating element which provides maximum heating output very quickly. The time required to reach the set temperature in this instrument was much smaller as compared to the traditional IR-technology. The instrument has gold-plated reflector plates to ensure better distribution of thermal radiation over the entire sample surface. The details of the unit were taken from operating manual [11].

The details of the halogen moisture analyzer unit used in this study are shown in Figure 1. This instrument allows setting of a drying method by specifying the set temperature and the switch-off criteria. The least count of the unit for weight measurement is 1 mg, the data was recorded at an interval of 1s for first one hour of the experiment, for the later period the data recording interval was 5s.

2.2 Materials and Experimental Procedure

Dried almonds (California grown) were obtained from local market. Almonds of similar size and each weighing 1 g ±0.07 g were segregated and used for the experiments. Drying experiments were conducted using multiple almond kernels. Objective of experiments was to analyses the moisture distribution across the almond kernels during the drying process. Two sets of configurations were used, a 2X2X2 total of eight almond kernels were placed in two layers. Four almonds in the bottom layer and four almonds in the top layer. Second configuration of 3x3x3, total of twenty seven almond kernels were used. There were three layers, each having nine almonds. Figure 2 (a) and (b) shows the arrangement of almonds for both these configurations. In order to keep the almonds intact during the experiments, individual almond kernel was glued using Feviquick. Dry weight of eight and twenty seven almonds were 8 g and 27 g, the corresponding weight of glue used were 0.5 g and 1.3 g respectively. Set of eight and twenty seven almond kernels was prepared and soaked in distilled water for a period of eight hours. The soaked block of eight and twenty seven almond kernels was independently dried using Mettler Toledo unit. Each experiment was carried out for a period of eight

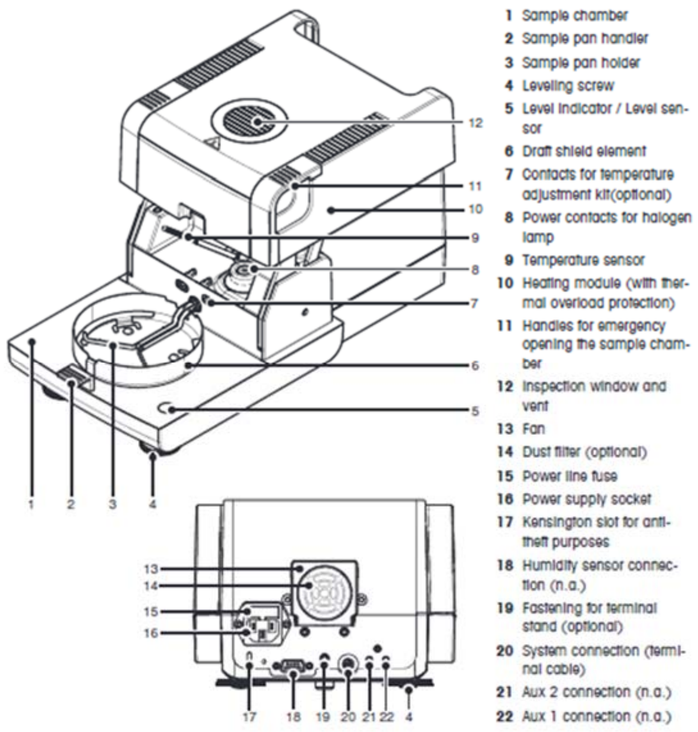


Figure 1. Schematic of Mettler Toledo Halogen Moisture Analyzer (HX204)

hours. Total weight of block was measured with respect to drying time for each experiment. Experimental data for weight loss with respect to drying from start to end of the experiments was recorded. Based on the total weight loss data, drying time corresponding to 80%, 60%, 40%, and 20% of weight loss was determined. Additional experiments were then conducted for each of these individual drying times. The objective of these experiments was to measure the moisture variation across all the individual almond kernels during the drying process. Individual almonds were separated to measure the weights and determine the moisture content of each almond. This data provided the moisture variation in almonds at top, middle and bottom layer during the drying process. Ten independent experiments were conducted for multiple almonds study.

3. Modeling of flow, heat transfer and drying in moisture analyzer

Figure 1 shows the schematic of Mettler Toledo unit which was used to perform experiments. Air through natural circulation enters and leaves the unit through vent openings located at the top. There are two flat plates on either side and two cylindrical plates on top and bottom, which forms a closed enclosure in the unit. A circular halogen lamp is the heat source to maintain set temperature in the unit. Due to the presence of temperature gradients buoyancy driven flow sets up in the unit. The natural convection flow field within the unit was simulated to study the air flow distribution around the almond kernels. Following are the modeling assumptions: (1) Steady state flow (2) Variation in size and shape of almond has negligible influence on surrounding air flow patterns (3) Adiabatic operation (4) Almond surfaces are impermeable for air flow and (5) There is no heat generation within the almond kernel.

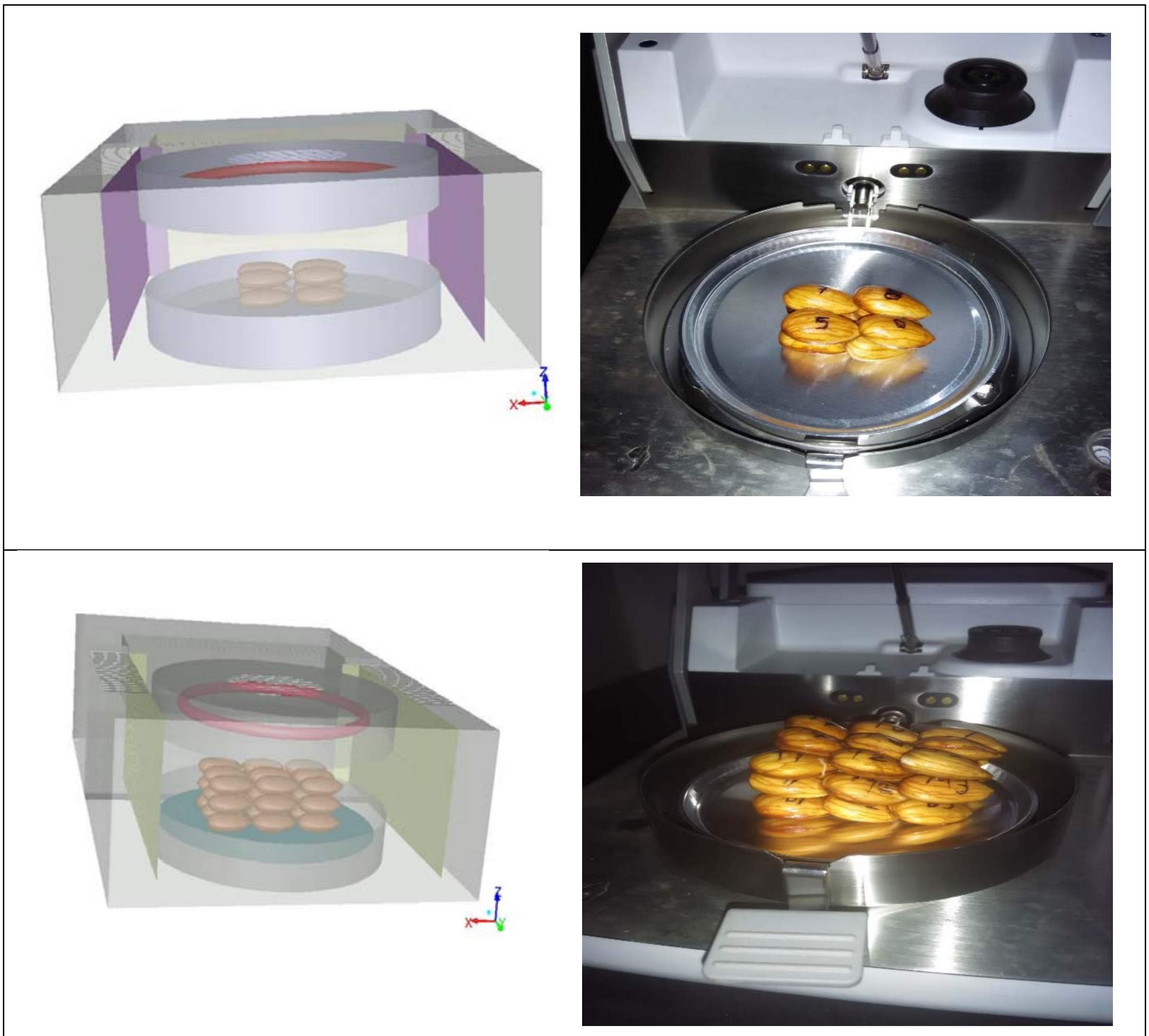


Figure 2. (a) CFD and Experimental model for 8 Almond Kernels, (b) CFD model for 27 Almond Kernels

3.1 *Model Equations*

Mass continuity, Momentum, energy and radiation equations were solved to simulate the flow and temperature distribution in the unit. The major mode of heat transfer from halogen lamp in the unit was radiation. Discrete Ordinate (DO) and Surface-to-Surface (S2S) are the two suitable models to capture the radiation heat transfer for this system. Based on the drying simulations of single almond kernel, it was determined that Surface-to-Surface (S2S) radiation model is more appropriate to capture the temperature distribution accurately in the unit. Equations are not being reproduced here, as the same could be obtained from [12]. To capture the natural convection flow profile within the unit, air density was modeled using incompressible ideal gas law equation. Steady state analysis is carried out for the flow and heat transfer in the unit, while transient analysis is carried out for the drying simulations.

User defined scalar (UDS) equation of ANSYS Fluent is used to solve for the moisture content in the almond kernel. UDS equation has an unsteady term, convective flux term and a diffusion term. The primary mode of moisture transfer within the almond kernel is diffusion. Only unsteady and diffusion terms were considered in the UDS equation. The reduced form of UDS equation for a scalar Φ, is:

$$\frac{\partial(\rho\emptyset)}{\partial t} = D_e\left(\frac{\partial^2\emptyset}{\partial {x_i}^2}\right) \quad (1)$$

3.2 *Estimation of Transport Properties*

3.2.1 *Estimation of Effective Diffusivity*

In order to determine the transport properties effective diffusivity is an important parameter which needs to be estimated. Experiments for single almond kernel were conducted at multiple temperatures to collect the drying kinetic data which was used to determine the effective diffusivity. Approximating almond kernel shape by an equivalent sphere, effective diffusivity was estimated using the Fick's second law of diffusion for spherical object as:

$$\frac{\partial c}{\partial t} = D_e\left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}\right) \quad (2)$$

Where r, is the radius of sphere, and c is local moisture content. For constant value of a diffusivity, the analytical solution is given by Crank [13]:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{D_e n^2\pi^2 t}{r_o^2}\right) \quad (3)$$

Where r_o is the radius of sphere.

Using above solution effective diffusivity for almond kernel was estimated considering the first ten terms of the analytical solution given by equation 3. Table 2. Contains the estimated effective diffusivity values for almond kernel, which was used in this work.

Table 2. Effective diffusivities for different drying temperatures

Temperature (K)	Effective Diffusivity x10^{10} (m^2/s)
328.15	2.67
338.15	3.19
348.15	4.83

3.2.2 *Estimation of Heat and Mass Transfer Coefficients*

Once the flow field and temperature profile in the unit is established, heat transfer coefficient profile on the almond surfaces was determined using the heat flux equation:

$$-\dot{q}_s = h(T_s - T_\infty) \tag{4}$$

Where $\dot{q}_s$ is the surface heat flux, T_s is almond surface temperature and T_∞ is the surrounding air temperature. Using the heat transfer coefficient profiles on the surfaces of almond kernel mass transfer coefficient profiles was calculated using the analogy between thermal and concentration boundary layers based on the expression given by Chilton and Colburn[14]:

$$k_m = h\left(\frac{DLe^n}{k}\right) \tag{5}$$

Le is Lewis number (ratio of thermal diffusivity to mass diffusivity). Higher the Lewis number faster will be heat transfer as compared to mass transfer. For almond kernel Le is around 233, hence thermal equilibrium is attained very quickly.

3.3 *Boundary and Initial Conditions*

Heat source for heating was supplied through a cylindrical halogen lamp located in the unit. Halogen lamp surface temperature was set to a constant value, in order to match experimentally measured air temperature.

To model the temperature variation within the almond kernel heat transfer coefficient profiles obtained from flow simulations along with surface temperature were specified.

For solving of moisture variation equation, specified flux boundary type was used for moisture equation, flux was given by:

$$-D\left.\frac{\partial m}{\partial n}\right|_s = k_m(M_s - M_a) \tag{6}$$

Where M_s is the surface moisture and M_a is the surrounding air moisture content.

Initial conditions:

Temperature: Almond kernel was considered to be at 25 ºC.

Moisture: Uniform moisture content was specified throughout the almond kernel

3.4 Computational simulations

Detailed geometry of the unit along with the almonds corresponding to the actual arrangement as shown in Figure 1 (a) and (b) for 2x2x2, 8 almonds and 3x3x3, 27 almonds configuration respectively.

Considering the detail geometry for all almonds, captures the natural convection driven flow pattern within the unit accurately. Based on the mesh resolution used for single almond simulations, fine mesh was generated for both the 8 and 27 almonds configurations. Computational geometry was built using Gambit 2.4, a product of ANSYS Inc [12].

Simulations were carried out using CFD Solver ANSYS Fluent release version 14.5. Second order discretization scheme was used for pressure, momentum, energy and radiation equations. SIMPLE algorithm was used for pressure-velocity coupling. Iterations were carried out till the residuals for all equations were below $1x10^{-5}$. Adequate care was taken to ensure that numerical aspects (number of computational cells, discretization schemes, convergence criteria) do not influence simulated results Ranade[15]. For computational models physical properties of food product is required to be used while solving the model equations. Aydin [16] has reported various physical properties for almond kernels. The values density [16], specific heat and thermal conductivity [17] for almond kernel used in the current work are listed in Table 1. The simulated results are discussed in the following section.

Table 1: Almond kernel properties

Properties	Value
True Density (Kg/m3)	1000
Thermal Conductivity (W/m-K)	0.2
Specific Heat (J/Kg-K)	2200

4. Results and Discussion

In the previous work on drying of single almond kernel, simulation results were validated against experimental measurements. Results showed significant upward air flow in the unit. Simulations of single almond nut were helpful in terms of developing the modeling approach and selection of relevant models to accurately predict the drying phenomena in the unit. Results in the form of velocity vectors, contours and temperature contours in the unit are used to analyze the flow and temperature distribution. Simulations have been carried out for the set temperature of 75 °C.

Buoyancy driven air flow has been generated in the unit, cold air enters from the sides and hot air exits from the top. Figure 3 (a), (b). Shows the velocity vectors on a center plane in the unit for 2x2x2 and 3x3x3 almonds configuration. On the outer boundaries of almonds relatively higher velocities exists as compared to the inside. The air also flows through gaps within the almonds. The air velocities on the outer side of almonds was in the range of 1.5 cm/s and air velocities within the gaps was around 0.8 cm/s. Movement of air flow helps to replace high humidity air out of the unit with fresh low humidity air in to the unit. For a single almond kernel case, the effective velocities around the particle were higher as compared to the multiple particle system, which promoted faster drying for single particle as compared to multiple particles.

As the heat source in the unit was supplied through a halogen lamp, which was modeled by setting a high surface temperature. Temperature profile in the unit with high temperature near the halogen lamp which reduces towards the inlet slots. Figure 4 (a) Shows the temperature distribution in the unit for 2x2x2 almonds configuration. It shows the temperature distribution around the almonds, air temperature gradually increases from inlet to outlet. The surface temperature of almonds was in the range of 60-68 °C. As the top layer was more close to the lamp and receives direct radiation from lamp it has relatively higher temperature as compared to the bottom layer of almonds. This in turn promotes relatively faster drying for top layer almonds. Temperature distribution on a center plane in the unit for 3x3x3, 27 almonds configuration as shown in Figure 4 (b). As there were three layers of almonds for this case, almond surface temperature of the top layer almonds was maximum, and minimum for the bottom layer of almonds. The simulations of multiple almonds provides details on variation of temperature profile over all the almonds.

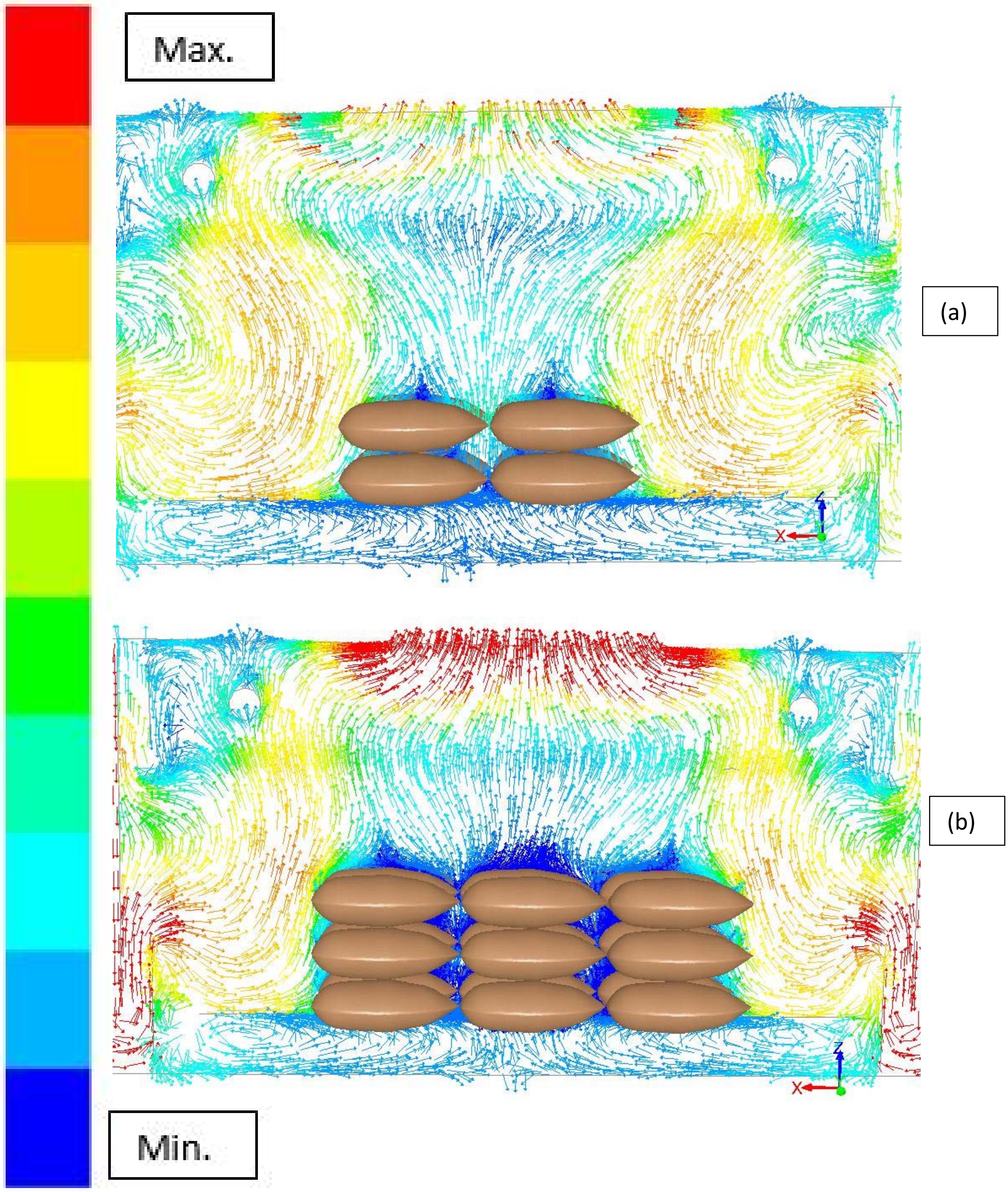


Figure 3. (a) Zoomed view of Velocity Vectors in the unit for 2x2x2 almonds (Min=0, Max=2 cm/s), (b) Zoomed view of Velocity Vectors in the unit for 3x3x3 almonds (Min=0, Max=2 cm/s)

The results also help to understand the relative drying rates across all the almonds. Drying simulations were carried out for both 8 and 27 almonds configurations, based on the modeling approach as developed during the drying of single almond simulations. Based on the obtained temperature field heat transfer coefficient profile over the almond surfaces was estimated. Heat transfer coefficient for individual almond was determined for 8 and 27 almonds configuration. Table 3 and 4 show the average heat transfer coefficient for all the almonds in 8 and 27 almonds configuration respectively.

Table 3: Average Heat Transfer Co-efficient for Individual 8 Almonds

Average Heat Transfer Co-efficient (W/m^2-K)			
Bottom		Top	
5.25	5.15	6.88	6.71
4.94	4.89	6.63	6.43

For both 8 and 27 almonds configuration it shows maximum heat transfer coefficient is for top layer and minimum for bottom layer of almonds. For 8 almonds configuration top almonds have about 25-30 percent more average heat transfer coefficient for top layer of almonds as compared to bottom layer of almonds. For 27 almonds configuration middle layer of almonds have about 30-40 percent higher average heat transfer coefficient as compared to bottom layer almonds. The top layer of almonds have about 80-90 percent higher average heat transfer coefficient as compared to bottom layer of almonds. As the drying rate changes with increase in the number of almonds for the same set temperature, a comparison of overall average heat transfer coefficient for single, 8 and 27 almonds as shown in Table 5. The overall average heat transfer coefficient decreases with increase in number of almonds. Maximum overall average heat transfer coefficient is for single particle and minimum for 27 particles.

Table 4: Average Heat Transfer Co-efficient for Individual 27 Almonds

Average Heat Transfer Co-efficient (W/m^2-K)								
Bottom			Middle			Top		
4.73	3.61	5.11	5.70	5.36	5.72	7.97	6.11	8.01
2.94	2.64	3.23	5.34	4.76	5.38	6.77	4.87	6.83
4.22	3.28	4.43	5.25	5.02	5.24	7.66	5.80	7.69

Table 5. Comparison of Overall Average Heat Transfer Coefficient for single, eight and twenty-seven Almond Kernels

Average Heat Transfer Co-efficient (W/m^2-K)		
Single	Eight Almonds	Twenty-Seven Almonds
6.2	5.86	5.32

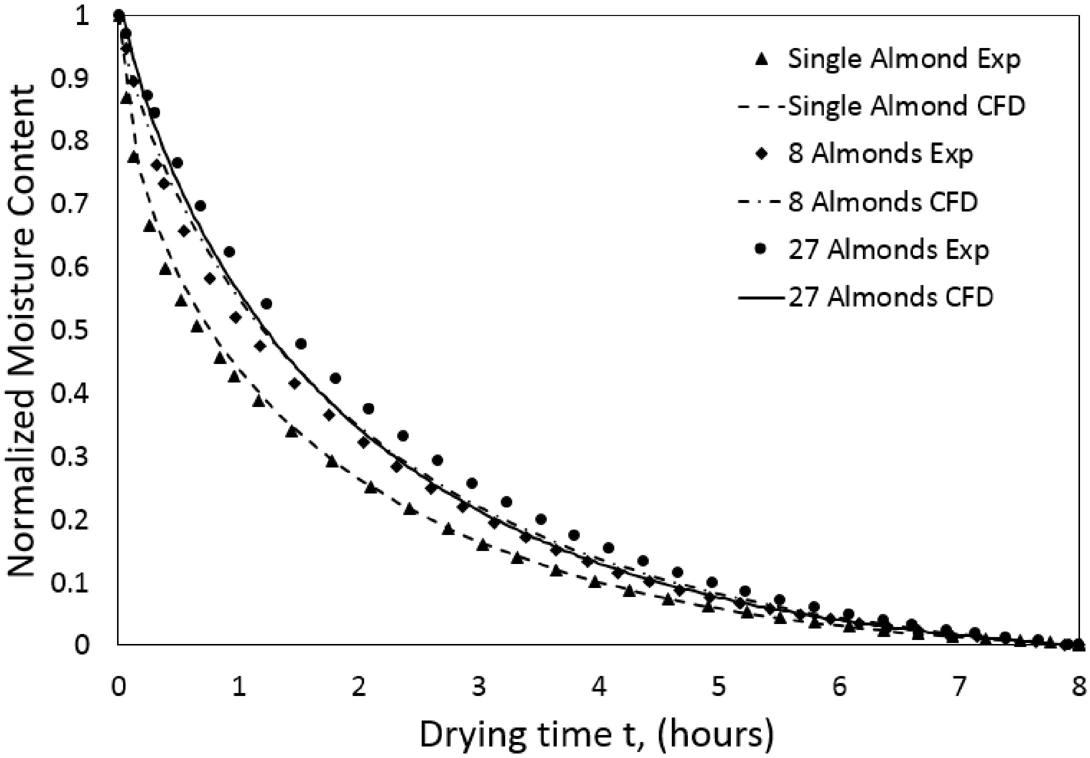


Figure 5. Comparison of Experimental drying data for single, 8 and 27 Almonds. and Comparison of Experimental and Predicted Average Moisture for 8 Almonds, and 27 Almonds

Transient simulations were carried out for drying of multiple almond configurations, for a drying time of 8 hours. Total average moisture content for all the almonds was monitored with respect to drying time. Figure 5 shows the comparison of experimentally measured average moisture content for single, eight and twenty seven almonds configuration. For a constant set temperature of 75 °C, drying rate decreases with increase in number of almonds. Drying rate of single particle is maximum, showing faster decrease in moisture as compared to eight and twenty-seven particles. Average moisture of all almonds based on experimental measurements and values predicted by simulations was compared for single, eight and twenty seven almonds as shown in Figure 5. The normalized moisture values for single almond is close to the corresponding experimental measurements. The normalized moisture plots for eight and twenty seven almonds is very similar, and overlap for a certain range of drying time. Since the temperature and heat transfer coefficient of top layer almonds was higher, this promoted faster drying of these almonds. Drying rate for top layer almonds was relatively higher as compared to other layers. A plane passing through all the layers of almonds was used to understand the moisture distribution. Contours of moisture distribution for 8 and 27 almonds as shown in Figure 6 (a) and (b) respectively. It shows that the top layer of almonds have relatively lower moisture content as compared to the bottom layer of almonds.

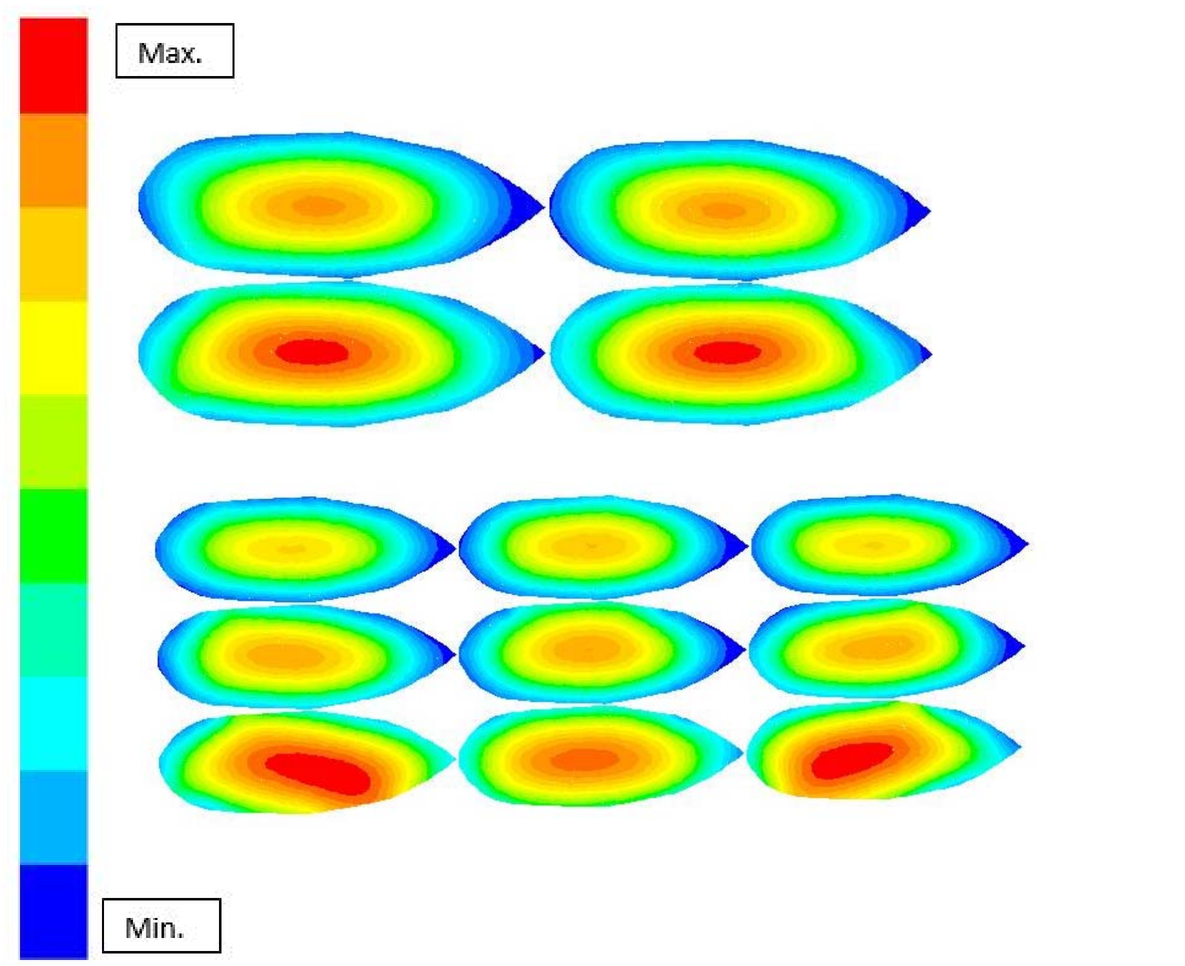


Figure 6. Moisture Contours during the Drying Process (a) 8 Almonds, (172 minutes, Min=0.01, Max=0.22) (b) 27 Almonds, (115 minutes, Min=0.01, Max=0.34)

Additional experiments were carried out to measure the moisture content of individual almonds during the drying process. Based on the complete drying curve, drying time corresponding to 80%, 60%, 40% and 20% of average initial moisture content was determined. Simulations were also stopped at these drying times. Average moisture content of each almond was determined for 8 and 27 almonds simulation results. Average moisture content of almonds in each layer was calculated based on the individual almond moisture content. For 2x2x2, 8 almonds configuration there are two layer, average moisture content for each layer was determined using the moisture values of four almonds. For 3x3x3, 27 almonds configuration there are three layers, average moisture content for each layer was determined using the moisture values of nine almonds.

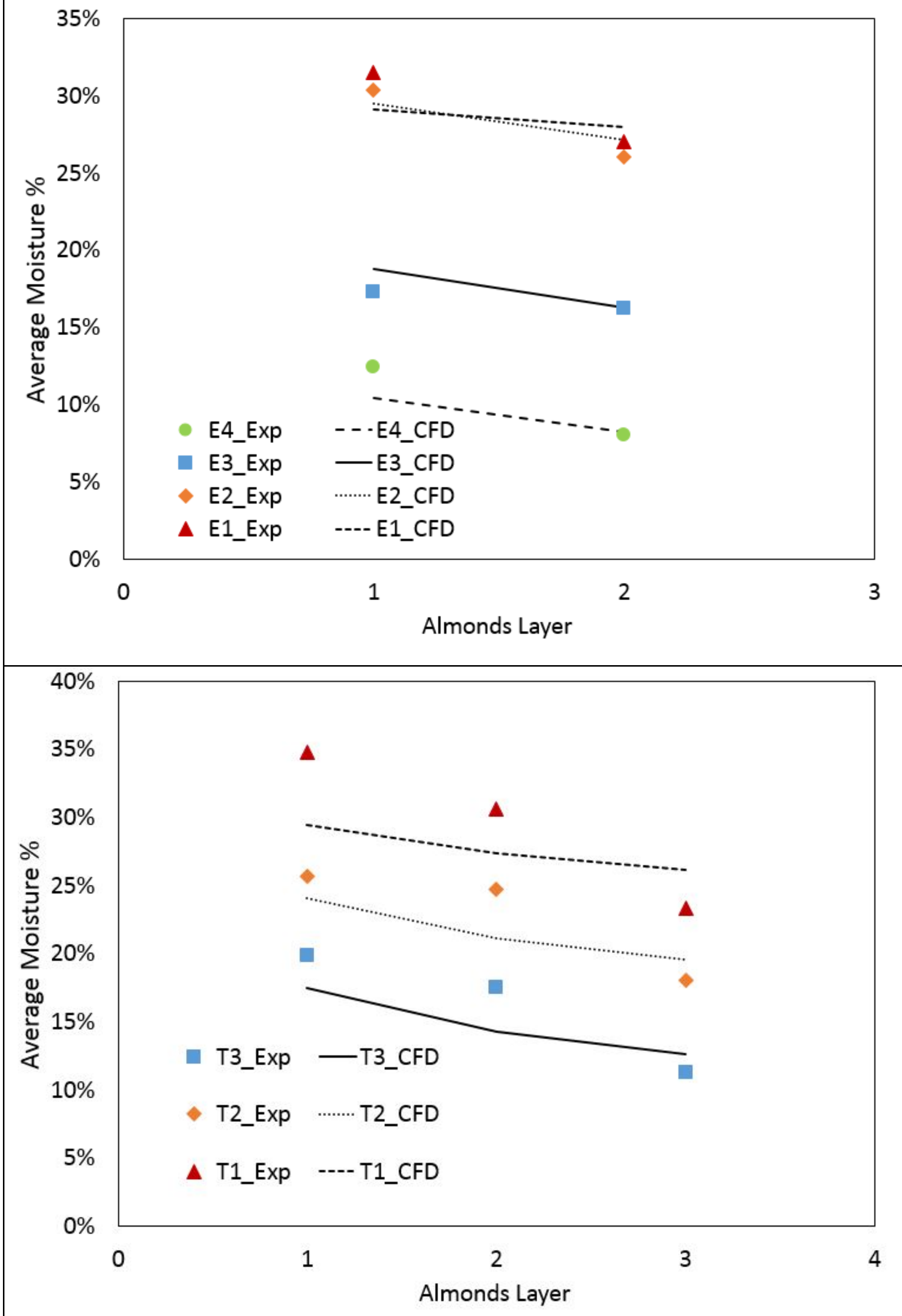


Figure 7. Comparison of Average Moisture during the Drying Process (a) 8 Almonds, (b) 27 Almonds

Comparison of average moisture values for each layer as shown in Figure 7 (a) and (b) for 2x2x2, 8 almonds and 3x3x3, 27 almonds respectively. Bottom layer is denoted by 1, top layer as 2 for 8 almonds configuration. For 27 almonds configuration 1 is for bottom layer, 2 is for middle layer and 3 for top layer. The drying experiments were stopped at intermediate drying times. E1, E2, E3 and E4 represent the drying time of 12, 35, 80 and 125 minutes respectively for 8 almonds configuration. Similarly T1, T2 and T3 represent drying time of 25, 60 and 115 minutes respectively for 27 almonds configuration. It shows that average moisture was higher for bottom layers as compared to top layers, also with higher drying times the difference between the layers also decreases. Results for multiple layers of rice grains studied by Perez et. al.[7] also showed similar pattern of higher temperature for layer which was near to heat source and relatively lower temperatures for other layers. There is some difference between the measured and predicted values of moisture content for both 8 and 27 almonds configurations. It should be noted that all the almonds were glued before starting the experiment. While weighing the almonds after drying, individual almonds were separated from the assembly. This separation was unfortunately not clean, that is because of the glue some part of the skin of almonds may not separate cleanly and may remain attached with other almonds. This leads to some change in weight, and hence the moisture content calculations. In CFD model there is a small gap between almonds in order to build computational mesh. This allows air to flow through the gap and absorb moisture and achieve lower moisture content than experimentally measured values.

Figure 8 (a) and (b) shows the average heat transfer coefficients for each layer for eight and twenty-seven particles respectively. This shows similar trend of top layer having higher heat transfer coefficient which will promote faster drying as compared to bottom layers of particles. This observation matches well with the previous published results by Perez et. al. [7].

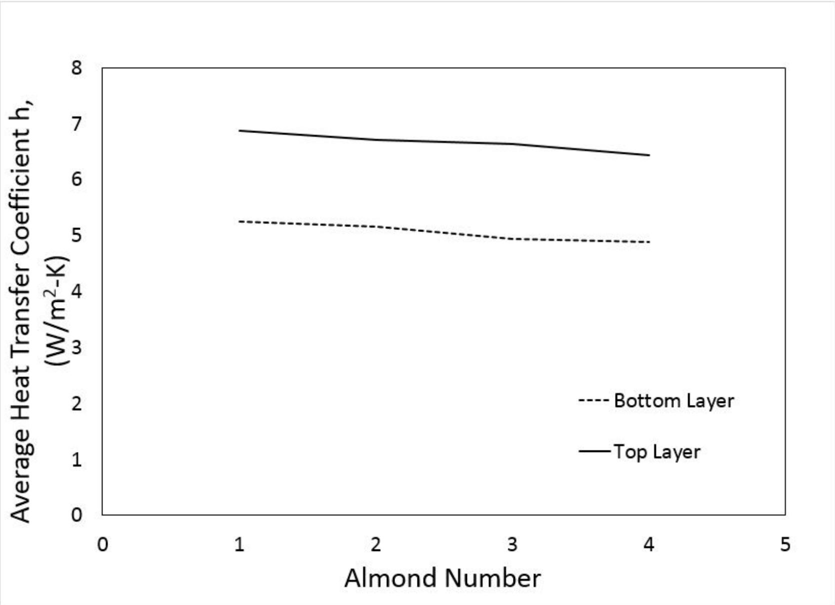
5. Conclusions

In this work drying characteristics for a multiple particles [eight (2x2x2) and twenty-seven (3x3x3)] of almonds was studied using experimental and computational modeling. Experimental data on drying of eight and twenty-seven particles was measured at a set temperature of 75 °C. The experimental data on variation of moisture content across all the individual particles was measured by stopping the experiments at drying times corresponding to 80%, 60%, 40% and 20% of average initial moisture. The CFD model was used to simulate the variation of heat and mass transfer coefficients for all the almond kernels for eight and twenty-seven almond kernels. Using the effective diffusivity estimated based on drying of single almond kernel was used to simulate and predict the moisture variation for all the almonds of eight and twenty-seven particle system. Average moisture content prediction of almonds for both eight and twenty-seven particle system was captured quite well in CFD model. The key conclusions of the work are:

- Presence of neighboring particles influences the drying kinetics, drying rate decreases with increase in number of particles for a given set temperature. For eight and twenty-seven particles system drying rate reduces to about 80% and 60% respectively, as compared to that of a single particle drying rate.
- Effective diffusivity estimated from single particle drying data is useful to predict the moisture variation for a multiple particles system

- The average transport properties decreases due to the influence of neighboring particles, which results in varying moisture content across individual particles. Overall average heat transfer coefficient for eight particles is 95% and for twenty-seven particles is 85% of single particle average heat transfer coefficient.
- Developed CFD model captures the overall moisture variation along with the moisture distribution across individual particles for intermediate drying times quite well

The developed modeling approach along with the average heat transfer coefficient values will be useful for simulating drying in large scale units.



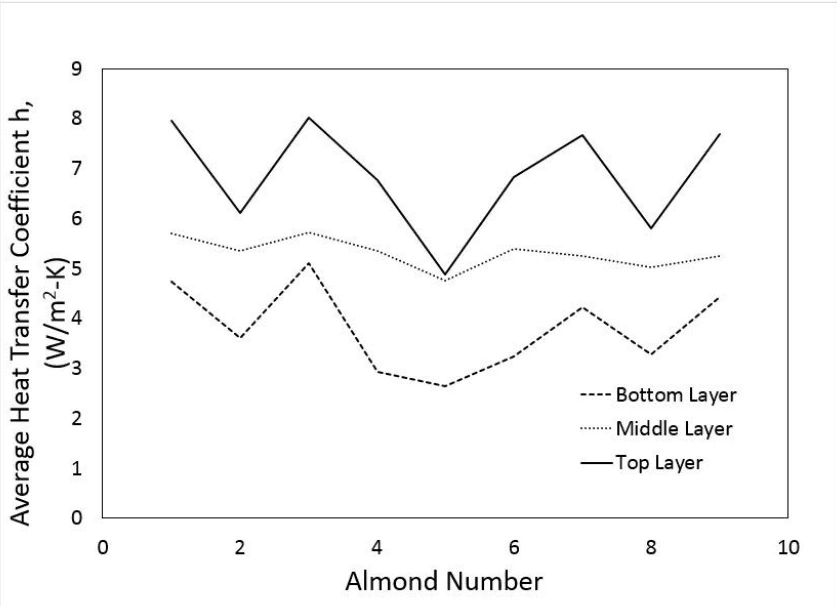


Figure 8. Variation of Average Heat Transfer Coefficient for Individual Almonds (single almond heat transfer coefficient: 6.2 W/m^2-K)

Nomenclature

q_s	surface heat flux, W/m^2
h	heat transfer coefficient, W/m^2-K
T_s	almond surface temperature, K
T_∞	free stream air temperature, K
K_m	mass transfer coefficient, m/s
Le	Lewis number
k	thermal conductivity, W/m-K
D_e	effective diffusivity m^2/s
M_s	surface moisture content, Kg/Kg solid
Ma	air moisture content, Kg/Kg dry air
MR	moisture ratio
t	drying time, s
n	model constant
r	radius of sphere, m

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